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Implementation of CNOSSOS-EU method for road noise in Italy

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ABSTRACT

The European Directive 2015/996 describes the common methods (CNOSSOS-EU) for the determination and management of environmental noise at European level, providing guidelines for a harmonized approach for Member States. CNOSSOS-EU includes different emission data for road, railway and industrial noise and provides a common model for sound propagation. The emission model was derived to be valid under reference conditions in terms of meteorology and traffic as detailed in the reference report by the Joint Research Centre (JRC) of the European Commission. In order to take into account situations that differ from the reference one, appropriate corrections were also offered. For a correct application on a local scale, the default values suggested by CNOSSOS-EU are required to be redefined in order to more adequately describe the Italian reality (i.e. car fleet, surfaces, climate conditions, etc.). Regional Agency for Environmental Protection of Tuscany (ARPAT) carried out specific measurements campaigns to acquire data useful to validate the methods for Italian conditions. Regression coefficients used in the emission model, were recalculated from campaigns in different sites carefully chosen to resemble the reference conditions.

Keywords: emission, database, CNOSSOS

1. INTRODUCTION

Directive 2015/996 (1) describes the common methods for determination and assessment of environmental noise at European level, providing guidelines for a harmonized approach of the Member States in order to identify priorities for action planning (aimed to reduce or avoid exposure to harmful noise levels) and by the European Commission (EC) to assess the number of people exposed to noise and to inform the general public about it.

These methods called "CNOSSOS" include separate calculation approaches for the emission of road, rail and industrial sources. Differently there is a common model for the propagation from the source to the environment. For aircraft noise, a separate emission and propagation model is defined, based on the ECAC Doc 29 requirements.

Particularly, for the noise produced by road infrastructures, the European intervention policies include, first and foremost, the progressive reduction of sound emission levels generated by vehicles and the interaction of tyres with road paving, therefore the intervention on the source is prioritized at the moment of the rehabilitation interventions.

The emission model was obtained from experimental measurements based on data sets of 4 – 10 years old in the framework of the IMAGINE – Harmonoise project (2). As a result, a set of sound power coefficients were obtained by means of regression analysis.

However, in the last years either the car fleet as the engineering technologies on pavement surfaces have evolved, therefore the coefficients proposed may have become obsolete. For a correct application on a local scale, the default values suggested by CNOSSOS-EU are required to be redefined in order to more adequately describe the Italian reality.

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2. CNOSSOS-EU

2.1 Emission Model

The sound power is calculated separately for the rolling noise generated by the interaction between the tire and the road $L_{wR\,f,m}$, and for the propulsion noise $L_{wP\,f,m}$ generated by the exhaust, engine, change of gear, etc.

$$L_{wR\,f,m} = A_{R,f,m} + B_{R,f,m} \cdot log\left(\frac{v_m}{v_{ref}}\right) + \Delta L_{WR,f,m}(v_m) \tag{1}$$

$$L_{wP\,f,m} = A_{p,f,m} + B_{P,f,m} \cdot \left(\frac{v_m - v_{ref}}{v_{ref}}\right) + \Delta L_{WP,f,m}(v_m) \tag{2}$$

Where the v_{ref} is set at 70 km/h and the coefficients $A_{R,f,m}$ and $A_{p,f,m}$ automatically assumes the meaning of average sound power level at the reference speed for the vehicle category in consideration, while the coefficients $B_{R,f,m}$ and $B_{p,f,m}$ determine the speed dependence. $\Delta L_{WR,f,m}$ and $\Delta L_{WP,f,m}$ correspond to the sum of the correction coefficients to be applied to the noise emission for specific conditions of the road or vehicle that deviate from the reference one.

CNOSSOS (3) provides four main categories of vehicles regarding their characteristics of noise emission. For the calculation of noise propagation and for the determination of sound power emission, it is necessary to describe the source with one or several point sources. In this method, each vehicle (category 1, 2 and 3) is represented by one single point source. As depicted in Figure 1, this point source is placed 0.05 m above the road surface

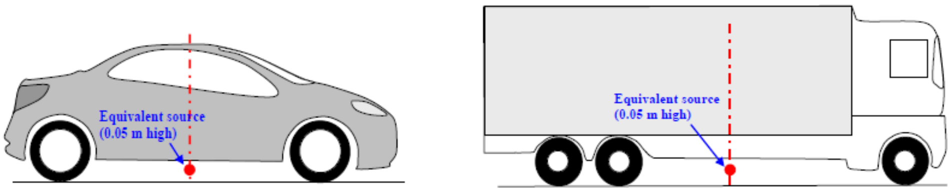

Figure 1 – Location of equivalent point source

The source equations and coefficients are derived to be valid under reference conditions in terms of meteorology and traffic.

2.2 Sound Power Coefficients

The sound power coefficients A_R, A_P, B_R and B_P for Eq. 1 and 2 have been obtained in the project IMAGINE (2). The distribution between rolling and propulsion contribution, was obtained by different measurement systems, i.e. on-board, coast-by or pass-by on test tracks and then calibrated using roadside pass-by measurements performed in different areas in the EU.

The IMAGINE model used a different source height composition:

- One source at 0.01 m height, to which 80% of the rolling noise and 20% of the propulsion noise was attributed.
- One source at 0.30 m height, for light motor vehicles and powered two-wheelers, or 0.75 m height for (medium) heavy vehicles, to which 20% of the rolling noise and 80% of the propulsion noise was attributed.

2.3 Free Field Propagation Model

The noise propagation model proposes the following equations concerning the different types of attenuation. The attenuation due to geometrical divergence, A_{div} corresponds to a reduction in the sound level due the propagation distance:

$$A_{div} = 20 \cdot log\,(d) + 11 \tag{3}$$

where d is the distance in meters between the equivalent source and the receiver. This equation regards to a point source in free field, with spherical divergence.

For the attenuation factor due to the absorption of the ground the following formulation have been proposed in the guidelines:

$$A_{ground} = max\left(-10 \cdot log\left[4\frac{k^2}{d_p^2}\left(z_s^2 - \sqrt{\frac{2\,C_f}{k}}\,z_s + \frac{C_f}{k}\right)\left(z_r^2 - \sqrt{\frac{2\,C_f}{k}}\,z_r + \frac{C_f}{k}\right)\right], -3(1 - G'_{path})\right) \tag{4}$$

Recently, the Netherlands National Institute for Public Health and the Environment (RIVM) have published a series of amendments for the CNOSSOS-EU (4). Among them, a correction in the A_{ground} formula was provided and new sound power coefficients suggested. For the A_{ground} the boundaries established by the term $-3(1 - G'_{path})$ in Eq. 4 was replaced by R in the Eq. 8

$$A_{ground} = 10 \cdot log\left(10^{-(A_{G,S}+A_{G,R})/20} + 10^{-A_D/10}\right) \tag{5}$$

$$A_D = 20 - 3 \cdot \log\left(\frac{f}{1000}\right) - 10 \cdot \log\left(\frac{d_p}{100}\right) \tag{6}$$

$$A_G = 20 \cdot log(1 + CR) \tag{7}$$

$$R = \min\left(\max\left(R_f, R_{min} = -0.9\right), R_{max} = 0.4\right) \tag{8}$$

Further studies proposed a simplification of the A_{ground} formula based on the coherent addition of the direct and reflected sound waves (5).

$$A_{ground} = -20 \cdot log\left(1 + \frac{R_1}{R_2} \cdot cos(k \cdot (R_1 - R_2))\right) \tag{9}$$

where R_1 and R_2 are the direct and reflected distances in meters. For further details, refer to (6), the official document of the method (3), and their amendments (4).

2.4 Transfer Function

In order to estimate the sound power levels from roadside measurements a proper transfer function was needed. In general, if the sound pressure is acquired for a single event, the associated sound power must be integrated along the time period T when the sound source pass-by is measured.

$$SEL_{pass-by} = 10 \cdot \log \int_{t1}^{t2} 10^{L_p(t)/10}\, dt \tag{10}$$

$$L_p(t) = 10 \cdot log_{10}\left(\frac{W}{W_o}\right) + 10 \cdot log_{10}\left(\frac{1}{4\pi r(t)^2}\right) + 10 \cdot log_{10}(DI) + 10 \cdot log_{10}\left(\rho_o\, c\, \frac{W_o}{{p_o}^2}\right) - A_{ground}(t) \tag{11}$$

Considering that at $\tau = 15\ °C$ and considering $\rho_o = 1.225\ kg/m^3$, $c = 340.5\ m/s$, then the terms $\rho_o\, c\, \frac{W_o}{{p_o}^2} \approx 1$ and $10 \cdot log_{10}\left(\frac{1}{4\pi}\right) \approx -11$.

Finally:

$$SEL_{pass-by} = 10 \cdot log_{10}\left(\int_{t1}^{t2} 10^{\left(L_W + 10 \cdot log\left(\frac{1}{r^2(t)}\right) + 10 \cdot log(DI) - 11 - A_{ground}(t)\right)/10} \cdot dt\right) \tag{12}$$

3. Methodology

Several sites were chosen with the premise to be sufficiently close to the source in order to carry out roadside Statistical Pass-By measurements (7), from now on called "SPB". Whenever it was possible the microphone was located at a distance equal to 7.5m from the road centreline and 4m height. Figure 2 shows the optimal set-up.

The SPB method is based on energy measurements associated with the passage of a single vehicle on a significant statistical sample. For each single event the time history of the levels, the spectrum in octave bands, the speed, the direction of travel and the distance between the axes, are acquired.

From an operational point of view, for each single passage and for each octave band, the single event level (L_{AE}), from now on called (SEL), was acquired on the entire time interval in which the signal exceeded the value of $L_{max} - 10dB$. For simplicity at the time of identifying the events, night-time measurements were analysed, where the vehicular flow was lower and the single events spaced over time.

For the classification of vehicle categories and the v_{ref}, a statistical approach was used on the distribution of distances between the measured axes and the speed distribution.

Regarding the weather data, the measurements days with rain and/or excessive wind (over 5 m/s), that could have influenced the results, were discarded.

For each experimental set-up and for each single event the different transfer functions were solved in order to obtain the sound power level at different heights from the SEL measurement. The obtained values were corrected for temperature.

Once the events were identified, classified by category, and the sound power levels calculated, a technique called "$\chi^2 - binned\ fit$" was used. Based on this procedure, the data was grouped into classes according to particular algorithms and each class was represented by a central value and an uncertainty associated, according to the distribution of data within each class (8).

Finally, the power levels were distributed proportionally in rolling noise and propulsion with two different approaches based on the quantity of the equivalent sources and their heights.

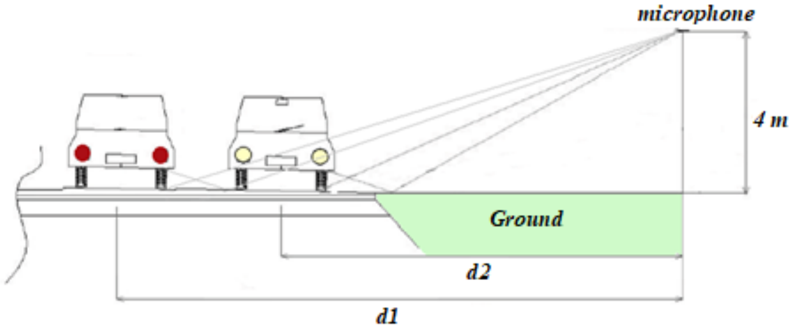

Figure 2 – Experimental set-up

4. Results

4.1 Transfer Functions

Following the above mentioned methodology, the critical aspect in this study was the resolution of the Transfer Function (from now on called TF). Recalling the Eq. 12

$$SEL_{pass-by} = 10 \cdot log_{10}\left(\int_{t1}^{t2} 10^{\left(L_W+10\cdot log\left(\frac{1}{r^2(t)}\right)+10\cdot log(DI)-11-A_{ground}(t)\right)/10} \cdot dt\right) \tag{13}$$

For simplicity's sake the $Directivity\ Index\ (DI)$ was assumed constant $DI = 1$, congruent with the hypothesis for an omnidirectional point source. For each single vehicle moving along the line in front of the microphone with a constant speed, the position x_1 at the instant t_1 and x_2 at t_2 are known. This allowed to introduce a change of variable.

$$x_2 - x_1 = x = vT \tag{14}$$

$$dx = vdt \tag{15}$$

$$r^2(t) = ({r_o}^2 + x^2) \tag{16}$$

being r_o the minimum distance between the source line and the microphone.

$$SEL_{pass-by} = L_W + 10 \cdot \log\left(\frac{1}{v}\int_{x_1}^{x_2} 10^{\left(-10\cdot\log({r_o}^2+x^2)-11-A_{ground}({r_o}^2+x^2)\right)/10} \cdot dx\right) \tag{17}$$

As detailed before three different formulations to consider the ground attenuation A_{ground} were studied, obtaining three different TF for each source height (0.01, 0.05, 0.3 and 0.75 m) with a fixed 4 m height receiver. Figure 3, Figure 4 and Figure 5 shows the TF in 1/1-octave bands, at 70 km/h and for a view angle of 160°.

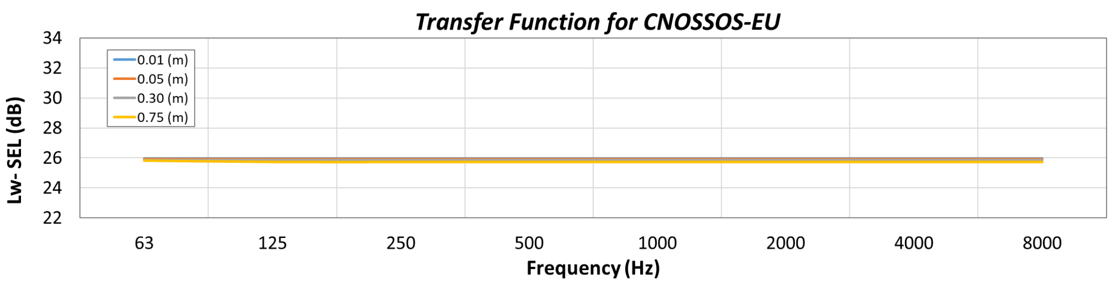

Figure 3 –Transfer Function using Eq. 4 for the A_{ground}

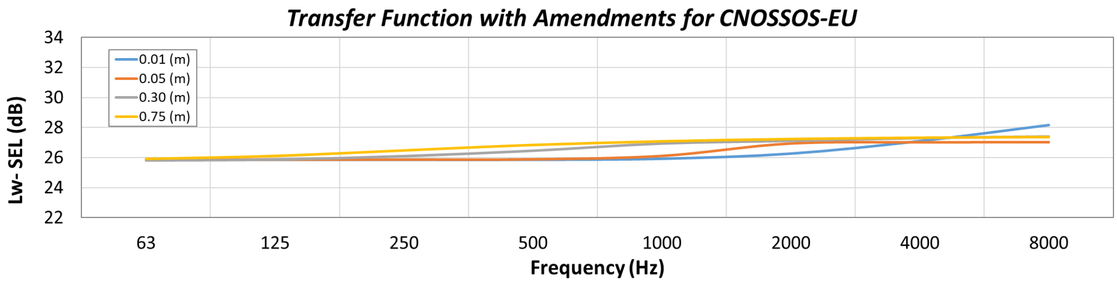

Figure 4 –Transfer Function using Eq. 5 for the A_{ground}

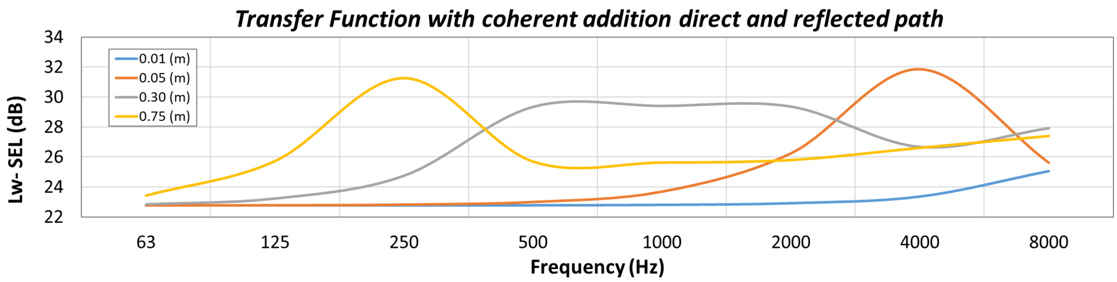

Figure 5 –Transfer Function using Eq. 9 for the A_{ground}

4.2 Sound Power Coefficients

Following the proposed work flow, once the TF were obtained, the "$\chi^2 - binned\ fit$" technique was applied. This procedure lies on a poissionan approach for the estimation of the uncertainty based on the count inside each bin, but this is useful when the number of occurrences is small. This is the typical case of the edge bins. Finally, the distribution of the sound power levels into rolling and propulsion components was carried out. Two different approaches were studied:

The first one consisted to use the source height composition as proposed in IMAGINE (2), for this approach the three transfer functions with the coherent addition of the direct and reflected rays $TF_{0.01}$, $TF_{0.30}$ and $TF_{0.75}$ were used to calculate the correspondent sound power levels, then the contributions were added as explained in 2.2.

The 2nd approach consisted to calculate the sound power levels at 0.05 m with the $TF_{0.05}$ assuming that the sound power of the source includes the possible effects of reflection on the surface immediately below the real source and in a specific direction in space, then the distribution into rolling and propulsion noise as proposed in CNOSSOS was carried out.

Figure 6, Figure 7 and Figure 8 shows the results for rolling, propulsion and total sound power levels for each category. In each graphic are plotted, the sound power levels obtained with the 1st approach called with the label "$\boldsymbol{TF_{coherence}}$, the sound power levels obtained with the 2nd approach and using the Eq. 5 called with the label "$\boldsymbol{TF_{Amendments}}$", the sound power levels obtained with the 2nd approach and using the Eq. 4 called with the label "$\boldsymbol{TF_{CNOSSOS}}$", the sound power levels suggested by CNOSSOS with an extra 3 dB addition with the label "***CNOSSOS Original Coeff +3 dB***" and the sound power levels suggested by the new amendments with the label "***CNOSSOS Amendments Coeff***".

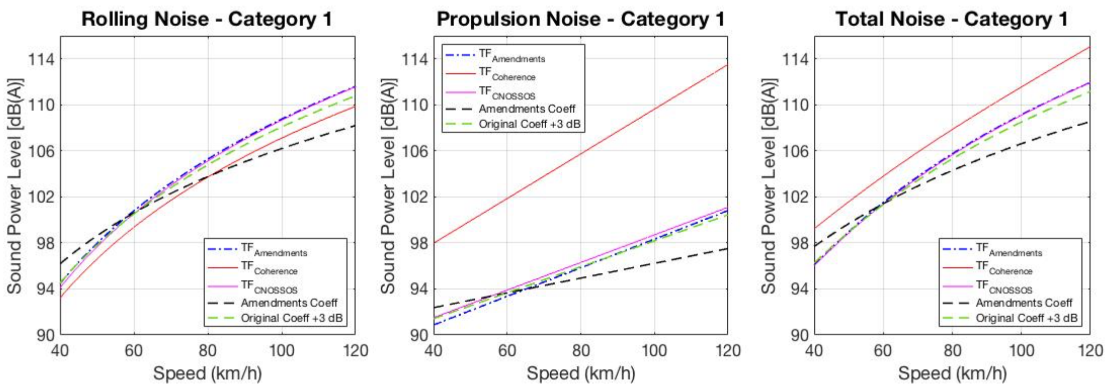

Figure 6–Rolling, propulsion and total sound power levels for category 1

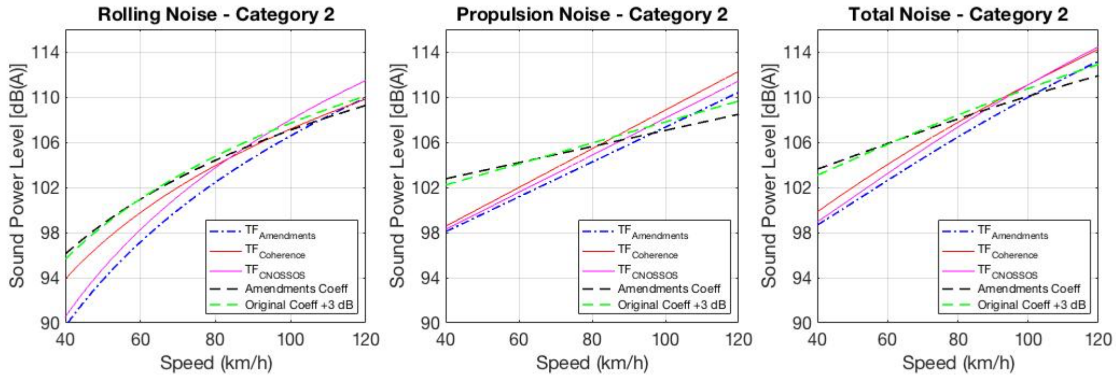

Figure 7–Rolling, propulsion and total sound power levels for category 2

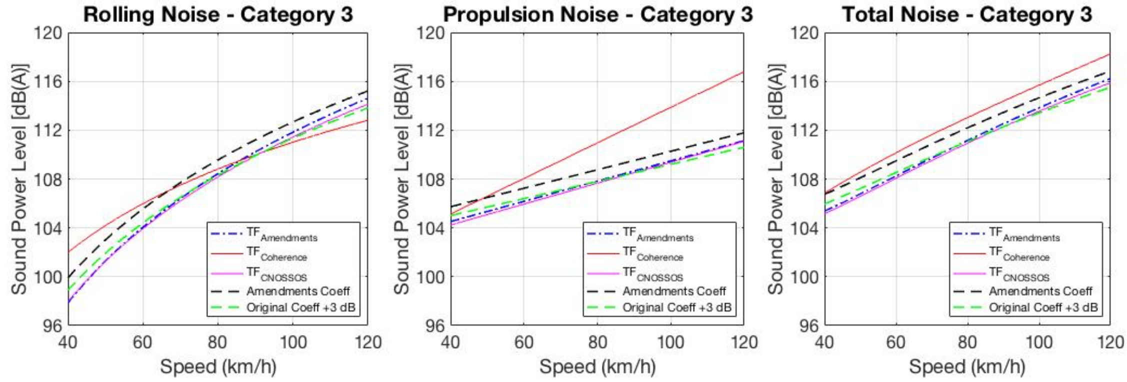

Figure 8–Rolling, propulsion and total sound power levels for category 3

The final coefficients for each category in 1/1-octave band obtained with the "$TF_{Amendments}$" and the 2nd approach are presented in Table 1, Table 2 and Table 3.

Table 1 – Coefficients for category 1

	63 Hz	*125 Hz*	*250 Hz*	*500 Hz*	*1000 Hz*	*2000 Hz*	*4000 Hz*	*8000 Hz*
A_R	85.1	86.8	88.6	94.5	101.2	96.4	84.6	74.9
B_R	40.3	42.3	32	26.5	35	39.6	41.8	44.2
A_P	99.7	90.3	92.2	89.9	88.1	89.4	83.7	76.5
B_P	3.2	8	5.4	9.3	8.8	8.8	9.1	9.9

Table 2 – Coefficients for category 2

	63 Hz	*125 Hz*	*250 Hz*	*500 Hz*	*1000 Hz*	*2000 Hz*	*4000 Hz*	*8000 Hz*
A_R	91.4	97.8	99.3	98.0	96.9	86.2	78.3	73.5
B_R	57.4	53.7	46.6	35.1	44.6	44.8	42.2	45.5
A_P	108.2	105.6	106.5	98.1	98.1	90.4	83.3	75.8
B_P	9.0	10.8	10.4	10.2	11.9	9.6	7.7	8.0

Table 3 – Coefficients for category 3

	63 Hz	*125 Hz*	*250 Hz*	*500 Hz*	*1000 Hz*	*2000 Hz*	*4000 Hz*	*8000 Hz*
A_R	94.1	93.8	97.3	104.2	103.8	96.1	88.2	84.3
B_R	49.8	30.4	9.7	30.4	38.7	34.5	28.8	31.3
A_P	111.9	102.9	105.2	104.5	103	97.8	92.4	87.2
B_P	12.2	4.2	-3.9	7	8.3	3.5	1.2	0.9

5. Discussions

5.1 Sound Power Coefficients

It has been shown in several studies that CNOSSOS-EU gives an underestimation of the noise levels up to 3 dB, this is explained because the source power coefficients were derived in the IMAGINE project with a different source composition as explained in 2.2. The problem lies in the fact that the propagation model was switched, and the equivalent source changed from to two to one. The CNOSSOS model adopts equivalents point sources being all mutually incoherent, while in the IMAGINE project coherent addition of the sources was assumed. In CNOSSOS the phrase "*The sound power of the source includes the possible effects of reflection on the surface immediately below the real source and in a specific direction in space*", implies that the presence of the reflective surface leads to a doubling of sound energy and an increase of the sound power of 3 dB.

For category 1 is known that at higher speeds, over 50 km/h, the contribution of noise is mostly a consequence of the tyre/road interaction and the aerodynamic noise, both considered in the rolling noise. This effect is consistent with the distribution assumed for light vehicles in the 2nd approach. When using the 1st approach for this category, the ground effects originated from the interference between direct and reflected path are strongly affected by the composition and variation in source height. For the propulsion noise it was considered a contribution of the 80% from the source at 0.30 m and 20% from the source at 0.01m. It can be observed in Figure 5 that there is a 7 dB difference between the the two sources in the frequency range between 500 and 2000 Hz, this produced an overestimation on the propulsion and the total sound power levels. Regarding the new formulation to take into account the grounds effects a slightly difference can be appreciated in the propulsion contribution, however as explained before the mainly contribution in this category comes from rolling noise.

For category 2 the methodology for classification exposed an important issue, a mixture between vehicles from category 1, 2 and 3. A deeper analysis showed two main clusters, the one with the lower slope after the "$\chi^2 - binned\ fit$" was chosen. It can be seen that the propulsion noise is predominant specially for low speeds. Considering that the speed range from the analysis is from 60 to 100 km/h, the proposed coefficients differ consistently in cases outside this range. Regarding the new amendments formulation, the results show a similar slope to the one obtained taking into account the coherence between direct and reflected waves.

For the category 3, the 2nd approach assume a predominant influence of the propulsion noise on the lower speed range and an inversion at the higher ones. Regarding the 1st approach, the source composition was assumed with the higher source at 0.75 m. As mentioned before this upper source have a bigger impact but at this particular height the peak is shifted to the lowers frequencies. It is important to highlight that higher sound power levels were expected, instead the results obtained for heavy vehicles were slightly lower than the ones proposed in the amendments. Again the range in speed is limited to 60 to 95 km/h.

Finally, we can appreciate that the results obtained with the 2nd approach for light and heavy vehicles are similar to the ones calculated with the original values with an addition of +3 dB.

5.2 Ground Attenuation

The latest amendments proposed a modification to the ground attenuation factor. In Figure 3 and Figure 4 the difference on the Transfer Function using one or another formulation can be observed, but these TF are a result of an integration along the distance travelled when the pass-by vehicle is measured, therefore the differences don't stand out. Remembering that the propagation model works on a point to point basis, Figure 9 is presented in order to elucidate the distinction between the new and the old formulation. The figures represent the ground attenuation factor as a function of the distance and frequency. It can be appreciated that the inferior boundary is represented by a flat surface. In the original formulation this surface was wider in the frequency range, up to 1000 Hz, and also in distance up to 40 m. Furthermore, in the new amendments the limit was reduced only to the lower bands, up to 125 Hz. Another observation is that peak was reduced in intensity and shifted in frequency, where in the original formulation the peak was up to 16 dB now is reduced at almost 8 db. Lastly, the ground effect is now wider than before affecting the whole frequency spectrum.

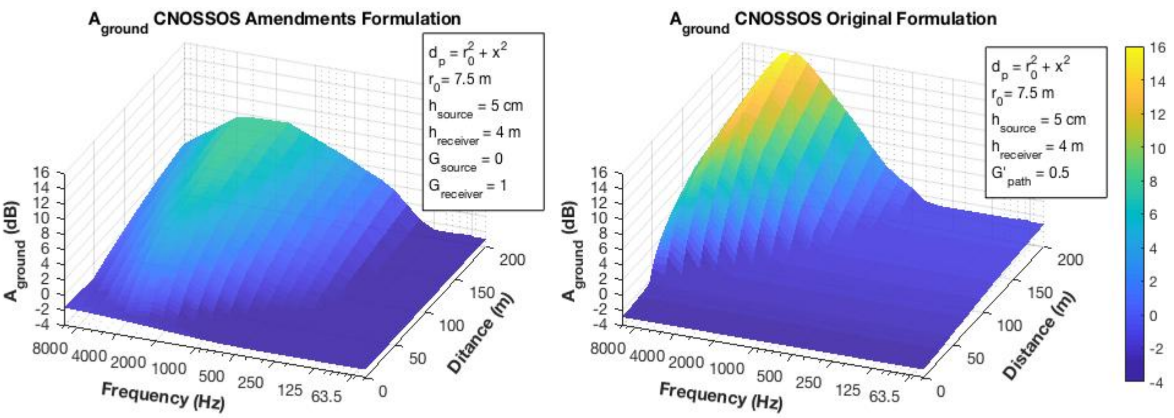

Figure 9–Attenuation Ground as a function of distance and frequency with Eq. 5 (left) and Eq. 4 (right)

6. Conclusions

Directive 2015/996 describes the common methods for determine and assess environmental noise at European level, providing guidelines for a harmonized approach of the Member States. These procedures called "CNOSSOS" include separate calculation methods for the emission and the propagation.

The emission model was obtained from experimental measurements based on data sets from IMAGINE project. As a result, a set of sound power coefficients were obtained by means of regression analysis. In this framework, the source composition was different, but in CNOSSOS the propagation model was switched, and the equivalent source changed from to two to one. This mismatch between the emission and the propagation model led to an underestimation of the noise levels up to 3 db.

For a correct application on a local scale, the default values suggested by CNOSSOS-EU are required to be redefined. A special methodology to derive the sound emission coefficients from regression analysis from the measurements was carried out. This methodology consisted to calculate the correspondent Transfer Function for each vehicle pass-by and then perform a "$\chi^2 - binned\ fit$".

The sound power levels were obtained using three different Transfer Functions considering the influence of the ground effect in different ways. Then the sound power levels were distributed to rolling and propulsion noise proportionally. Final results for category 1 and 3, using the "$\boldsymbol{TF_{Amendments}}$" presented a similar trend to the original coefficients suggested with a difference of +3 dB.

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